TECHNICAL REPORT ARCCB-TR-93030

# INCREASING MISSION RELIABILITY USING OPEN-LOOP CONTROL

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AUGUST 1993

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# REPORT DOCUMENTATION PAGE

Form Approved
OMB No. 0704-0188



| 1. AGENCY USE ONLY (Leave blank) | 2. REPORT DATE | 3. REPORT TYPE AND DATES COVERED |
|---|---|---|
| | August 1993 | Final |

**4. TITLE AND SUBTITLE**
INCREASING MISSION RELIABILITY USING OPEN-LOOP CONTROL

**5. FUNDING NUMBERS**
AMCMS No. 6126.24.H180.0

**6. AUTHOR(S)**
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**7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)**
U.S. Army ARDEC
Benet Laboratories, SMCAR-CCB-TL
Watervliet, NY 12189-4050

**8. PERFORMING ORGANIZATION REPORT NUMBER**
ARCCB-TR-93030

**9. SPONSORING / MONITORING AGENCY NAME(S) AND ADDRESS(ES)**
U.S. Army ARDEC
Close Combat Armaments Center
Picatinny Arsenal, NJ 07806-5000

**10. SPONSORING / MONITORING AGENCY REPORT NUMBER**

**11. SUPPLEMENTARY NOTES**
Submitted to *IEEE Transactions on Reliability*.

**12a. DISTRIBUTION / AVAILABILITY STATEMENT**
Approved for public release; distribution unlimited.

**12b. DISTRIBUTION CODE**

**13. ABSTRACT** *(Maximum 200 words)*

This report proposes to increase the reliability of some single-degree of freedom servo systems by providing a degraded mode of operation in the event of feedback sensor failure. Normally, the system is operated in a closed-loop feedback mode. During normal operation, information is continuously gathered on the disturbing forces encountered and their statistical variations from cycle-to-cycle. This information is used to design an open-loop controller that can take over in the event of sensor malfunction.

An ideal closed-loop controller for this purpose is the modified bang-bang controller because the operating cycle for this controller is readily divided into three sections: acceleration, constant velocity, and deceleration. Disturbing forces can be estimated in the three sections. The *s*-mean and *s*-variance of the disturbing forces can then be used to design a conservative open-loop cycle. The cycle is conservative in that the target position for open-loop is less than the desired target position by an amount that yields a specified small probability of exceeding the desired target at some specified *s*-confidence level. The total cycle is then finished using a constant or cyclic motor force or other technique depending on the specific application. We successfully applied the developed techniques to the loading cycle of a large caliber tank ammunition autoloader.

**14. SUBJECT TERMS**
Mission Reliability, Feedback, Sensor Failure, Modified Bang-Bang Control, Open-Loop Control

**15. NUMBER OF PAGES**
22

**16. PRICE CODE**

| 17. SECURITY CLASSIFICATION OF REPORT | 18. SECURITY CLASSIFICATION OF THIS PAGE | 19. SECURITY CLASSIFICATION OF ABSTRACT | 20. LIMITATION OF ABSTRACT |
|---|---|---|---|
| UNCLASSIFIED | UNCLASSIFIED | UNCLASSIFIED | UL |

NSN 7540-01-280-5500

Standard Form 298 (Rev 2-89)
Prescribed by ANSI Std Z39-18
298-102

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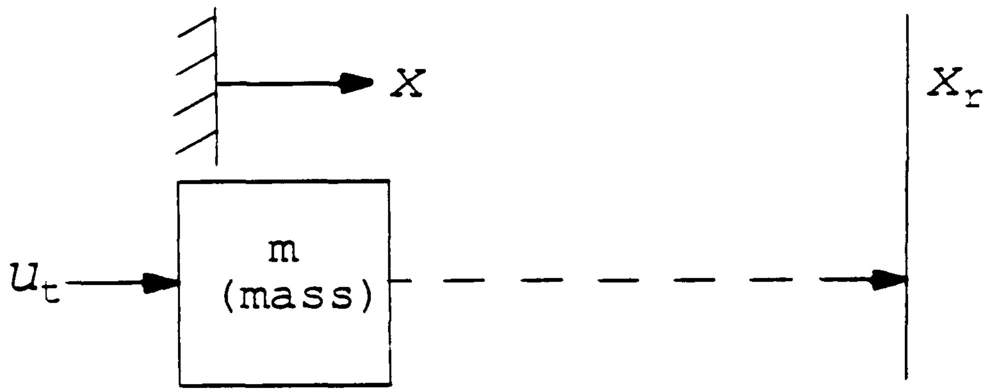
## NOTATION AND ACRONYMS

| | |
|---|---|
| MBB | modified bang-bang (controller) |
| PD | proportional-derivative (controller) |
| $\bar{v}$ | a bar over a variable implies average value of a random variable |
| $\tilde{v}$ | a tilde (˜) over a variable implies a sample outcome of a random variable |
| $C$ | % confidence level |
| $F$ | friction force |
| $k_1,k_2$ | positional and velocity gains |
| $m$ | mass |
| $t$ | time |
| $t_p$ | non-central Student t parameter |
| $u$ | servomotor force |
| $u_d$ | disturbing force |
| $u_g$ | gravity and/or coupling force |
| $u_m$ | specified maximum motor force |
| $u_t$ | total force acting on mass $m$ |
| $x,v$ | position and velocity of mass $m$ |
| $x_r$ | desired or command position of mass $m$ |
| $v_m$ | specified maximum velocity of mass $m$ |
| $\sigma_{var}$ | standard deviation of random variable *var* |

## INTRODUCTION

The main objective of the work presented in this report is to increase the mission reliability of a one-degree of freedom computer-controlled servo system. This is to be accomplished by providing an acceptable degraded mode of operation that can take over functioning of the system in the event of feedback sensor failure. The failure mode can be either the total loss of position/velocity feedback or unacceptable instability resulting from such effects as high backlash, partial loss of signal, or sudden high feedback noise. We have experienced all of these failure modes in our development of a large caliber tank autoloader. The proposed degraded mode of operation to be used in the event of feedback failure is open-loop control (refs 1,2). Open-loop control eliminates many controller-based instabilities and permits operation of a servomechanism with minimal or no feedback.

It might be helpful at this point to briefly discuss servocontrol for those who are not servo experts. The main objective in servocontrol is to move a given mass using motor forces. A simple one-degree of freedom force-mass system is shown in Figure 1. A mass $m$ is subjected to a total force $u_t$, which may be a function of time, position, and/or velocity. This force is comprised of a motor force $u$ and a force term we will call a disturbance force $u_d$. The disturbance force is comprised of all other forces that are not motor forces. These include such things as friction, gravity, and inertial coupling. One objective of servocontrol is to drive a mass $m$ from one position to another, say $x$, as shown in Figure 1, using the motor force $u$, overcoming any disturbing forces $u_d$ that might be encountered during the motion cycle.




$$u_t = u(motor\ force) + u_d(disturbance)$$
$$= m\ddot{x}$$

Figure 1. Elementary one-degree of freedom control problem.

We can control the motor force using a computer and electronic hardware that converts and amplifies computer commands into motor forces. Position and velocity sensors can be used to provide real-time information to the computer controller as shown in Figure 2. We can now employ different kinds of control laws to determine the motor force $u$ as a function of time and feedback signals $x$ and $\dot{x}$ (refs 1,2). If the feedback information of position and/or velocity is used in the control law, this is termed closed-loop control. If no feedback is used, it is termed open-loop control.

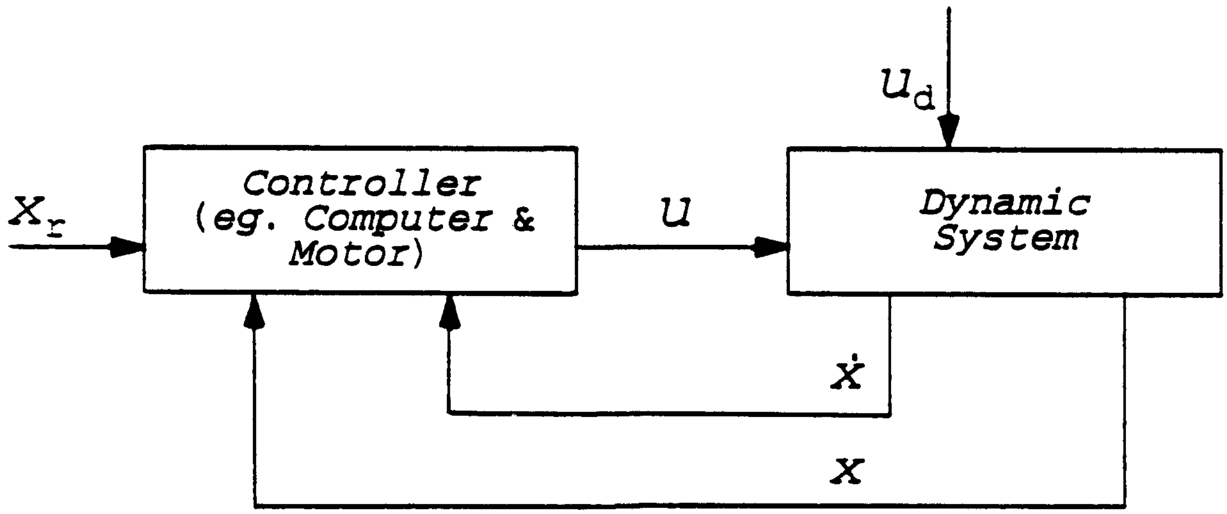



Figure 2. Feedback servocontrol.

In this report, we only consider the problem of positioning a one-degree of freedom system. Decoupling a multi-degree of freedom system will be considered in the future. The basic idea is to normally run the system using closed-loop if there are no feedback sensor failures. In many servo systems, the most significant cycle-to-cycle unknowns are the disturbing forces such as friction, gravity, motion coupling, etc. In the closed-loop system, the unknown disturbing forces are automatically taken care of as part of the control law and feedback process. The disturbing forces and their statistics can be estimated during normal operation of the closed-loop system by observing actual motor forces versus response. The calculated statistical means and variances of the disturbing forces can then be used to design a conservative open-loop controller using the procedure described in this report. Then in the event of feedback failure, the conservative open-loop controller can take over to drive the system short of, but as near as possible, to its final position with low probability of excessive overshoot or collision. The cycle is then finished using a constant or cyclic force or some other means depending on the application.

An ideal closed-loop controller amenable to designing an open-loop system is the modified bang-bang (MBB) controller (refs 3-6). In its simplest configuration, the MBB controller is comprised of three basic phases: acceleration, constant velocity, and deceleration. An open-loop system can then be designed using these three motion phases. Disturbing forces in the three phases are estimated from previous closed-loop runs and used to determine constant motor force levels and times of application to complete the required motion for open-loop operation.

We successfully applied the developed open-loop techniques to a large caliber tank cannon autoloader (ref 7). A schematic diagram of the XM98 140-mm tank autoloader is shown in Figure 3. The autoloader shown here is comprised of a 17-cell carousel ammunition storage and repositioning system (only two cells are shown in the figure) and a loading mechanism. The loading mechanism is comprised of two servo systems: a telescoping cell and rammer. The telescoping cell is used to bridge the gap between the ammunition storage area in the bustle of the tank turret and the breech end of the gun tube. The ramming mechanism pushes the round of ammunition from the storage position through the telescoping cell and into the gun tube. Both servo systems use MBB control. Data from cycling the ramming mechanism were analyzed to determine the unknown disturbing forces, primarily friction, in the three main control phases. An open-loop system was then successfully run using the generated data. Details of these tests are discussed later in the report.

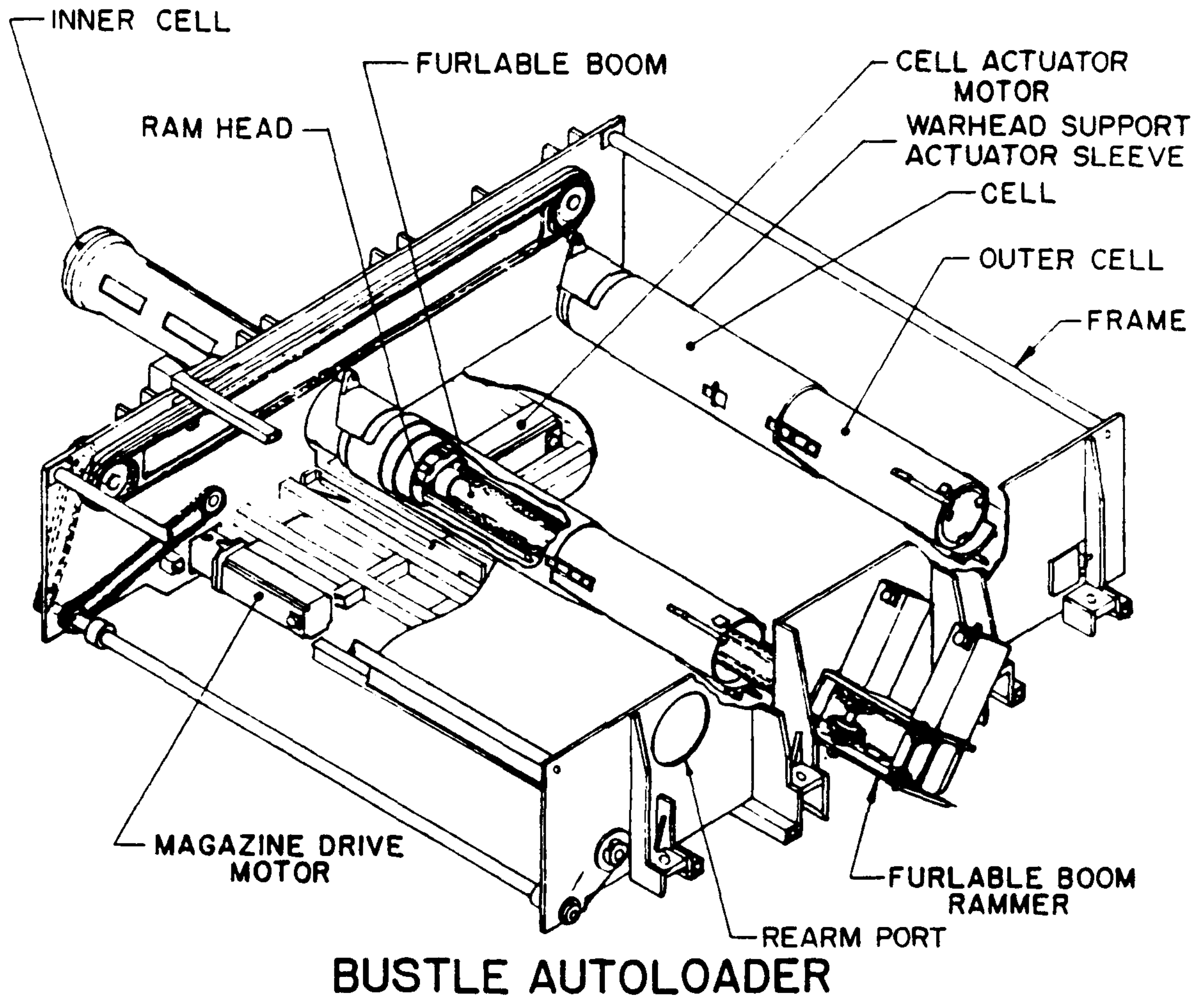



Figure 3. Schematic of XM98 140-mm tank autoloader.

The remainder of this report is outlined as follows:

- Description of the problem
- Designing an open-loop system
- Statistics of final position and velocity for open-loop control
- Measurement of disturbing forces from closed-loop MBB control data
- Experimental results for large caliber autoloader

## DESCRIPTION OF THE PROBLEM

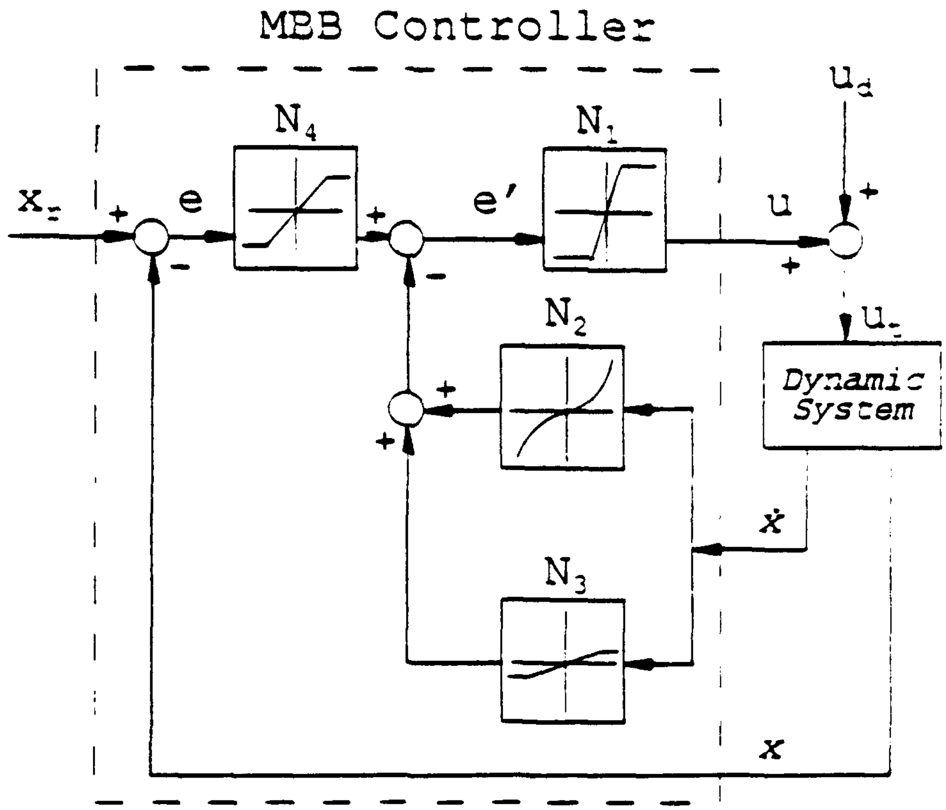
Consider the positioning problem of a one-degree of freedom system using MBB control. Equation (1) describes the equation of motion for a typical simplified system:

$$u + u_d = m\ddot{x} \tag{1}$$

| | | | |
|---|---|---|---|
| in which | $m$ | = | mass |
| | $x$ | = | position of mass $m$ |
| | $u$ | = | servomotor force |
| | $u_d$ | = | random disturbing force |

The closed-loop control approach used in this study is the MBB controller, which is also called switching zone controller elsewhere (refs 3-7). The MBB controller is based in part on the bang-bang theory in which maximum allowable torques are applied to both accelerate and decelerate a mechanism to move from one position to another in near minimum time. Essentially, the MBB controller is comprised of bang-bang control with a boundary layer away from the desired target position and then a transition to proportional-derivative (PD) control near the target position (refs 1,2). A maximum velocity is often specified as a design requirement.

The schematic diagram for the MBB controller is shown in Figure 4, where the dynamic system is described as equation (1).




$$N_1: \quad u = k_1 e'; \quad (-u_m < u < u_m)$$
$$N_2: \quad out = (m/2au_m)\,|\dot{x}|\,\dot{x}$$
$$N_3: \quad out = k_2\dot{x}; \quad (-b < out < b)$$
$$N_4: \quad out = e; \quad (-\xi_1 < e < \xi_1)$$
$$\xi_1 = b + (m/2au_m)\,v_m^2$$

Figure 4. Block diagram of modified bang-bang controller.

The different controller variables and parameters are defined as follows:

| | | |
|---|---|---|
| $m$ | = | system mass |
| $x$ | = | position of the mass |
| $x_r$ | = | desired position |
| $u$ | = | motor force applied to mass $m$ = torque/lever arm |
| $u_d$ | = | disturbing force |
| $u_m$ | = | specified maximum motor force or torque |

$a$ = nonlinear function term selected to guarantee sufficient force for deceleration

= $(u_m - u_{dm})/u_m$, where $u_{dm}$ is the maximum value of the disturbance force $u_d$

$b$ = constant selected to guarantee no overshoot,

= $2au_m/k_1$

$k_1, k_2$ = positional and velocity gains

$\xi_1$ = $b + mv_m^2/(2au_m)$

where $\xi_1$ is essentially dependent on the specified maximum velocity $v_m$

Figure 5 shows position, velocity, and motor force as a function of time for an example of an ideal control case where no feedback noise exists. Actual data for the ramming cycle of a tank autoloader is shown in Figure 6, where acceptable noise effects are present in the feedback and hence in the motor forces.

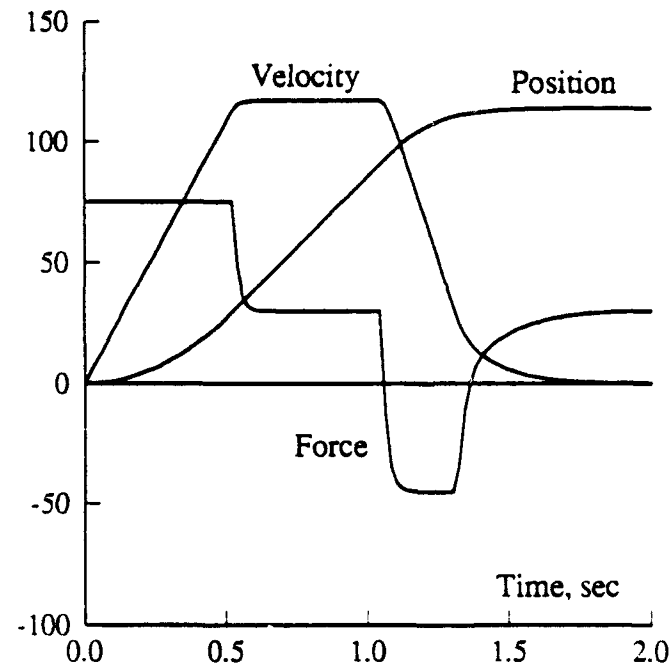



Figure 5. Example of an ideal modified bang-bang control case.

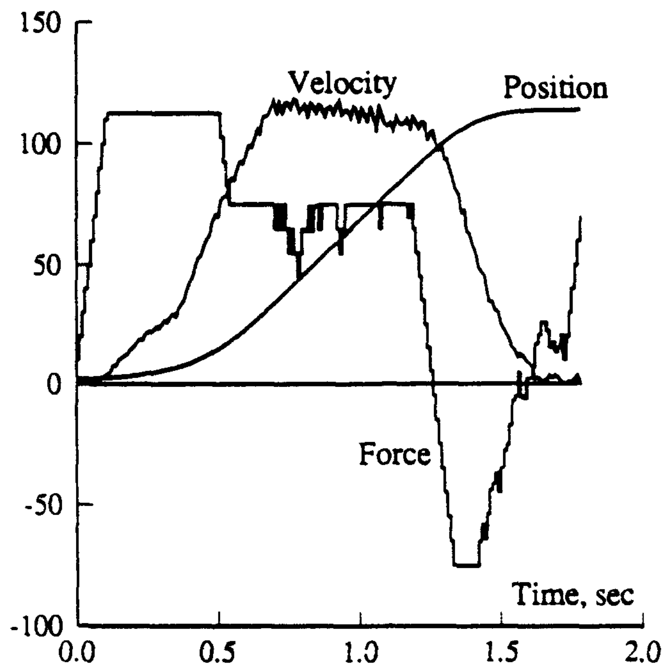



Figure 6. Experimental data for large caliber autoloader....ramming cycle.

The main problem considered in this report is the following: if there is a loss or degradation of feedback, can we still complete a positioning cycle using another control mode? In the case of the autoloader, can we still load ammunition and complete a firing mission? The technique considered here to accomplish this is to use open-loop control, which does not require feedback information. It is proposed to use the motor force versus time histories of the closed-loop system to generate a motor force profile that can be used in an open-loop mode if required. This is discussed in the next section.

## DESIGNING AN OPEN-LOOP SYSTEM

An ideal open-loop profile is shown in Figure 7. Constant motor force is applied in each of the three sections shown in this figure. The time intervals for force application depend on the disturbing force and other fixed parameters of the system. Ideally, the system is accelerated in section 1 to a maximum specified velocity $v_m$. The motor force is then reduced to a value that just overcomes the disturbing force in section 2 to maintain a constant velocity. Finally, a negative constant force is applied to decelerate and stop the system at the desired target position with the velocity going to zero.

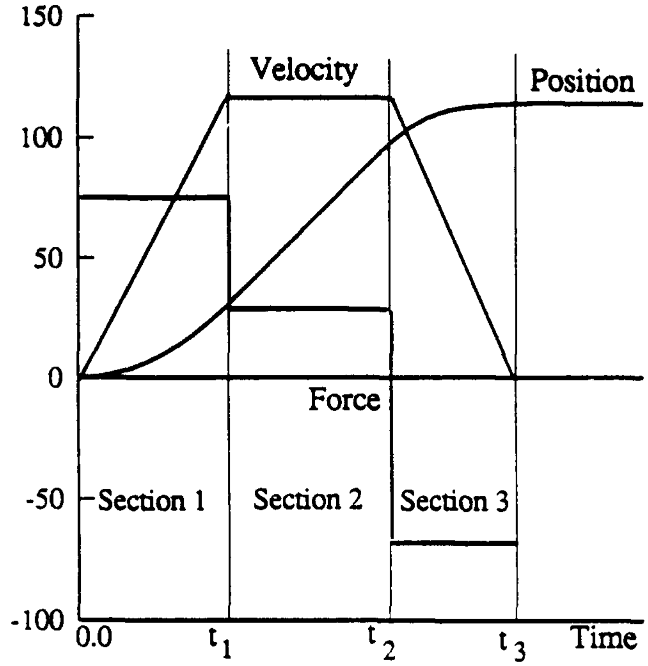



Figure 7. Ideal open-loop profile of constant motor forces.

In the actual non-ideal case, the disturbing forces in the three main sections of Figure 7 are random variables. From a number of closed-loop trials, we can estimate the *s*-mean and *s*-variance of the disturbing forces in the three control sections. The average value of the disturbing forces is then used to estimate the times $t_i$ for the three sections. However, since the disturbing forces are random variables, the actual final position and velocity for open-loop control of our system will be random. We, therefore, propose to choose a *conservative* target position $x_{r_o}$ (*o* indicating open-loop) that is less than the actual desired target point $x_r$. This new target position is chosen so that the probability of exceeding the original $x_r$ in any given random cycle using open-loop control is some small acceptable value, for example 5 percent or 10 percent at some given *s*-confidence level. At the end of the open-loop cycle, some other procedure may need to be initiated to finish off the total cycle. For example, a constant positive force may be applied for a given period of time or until a switch is tripped indicating completion. In the case of the autoloader, there are hard stops at the end of a loading or unloading cycle. Some final docking velocity is acceptable in this case as long as it is not too large. Also, there is some desired final docking force that can be applied at the end of the total operation. The final procedure required depends on the actual system to be controlled and on experimentation to determine acceptable final velocities and forces.

We are only concerned here with designing the original open-loop cycle portion of the total operation. From a number of closed-loop trials, we estimate the random disturbing forces in the three sections of Figure 7 as discussed earlier. For a reasonably large sample size, we can estimate the *s*-means and *s*-variances of the disturbing forces. From the statistics of the frictions and other disturbing forces, we estimate the statistics (e.g., *s*-mean and *s*-variance) of the final random position $x_f$ for open-loop operation. We can accomplish this by assuming the *s*-normal distribution for disturbing forces and then using either Monte Carlo simulation or theoretical derivations, as will be presented in the next section of this report. Once we know the statistics of the final position, we can estimate the new target position $x_{r_o}$ using the sample *s*-mean and *s*-standard deviation of $x_f$,

$$x_{ro} = x_r - t_p \sigma_{x_f} \tag{2}$$

In equation (2), $t_p$ can be determined from the non-central $t$-distribution for a given probability $p$ and $s$-confidence level $C$ (refs 8,9). This is assuming that $x_f$ is $s$-normally distributed. $t_p$ is the number of sample standard deviations required to yield $p$ probability that a random variable $\tilde{x}_f > x_r$. For example, for $p$ = 10 percent and $C$ = 90 percent, $t_p$ = 2.065 and 1.657 for sample sizes of 10 and 30, respectively.

In the next section, we present the derivation of $\sigma_{x_f}$ as a function of the distribution and statistics of the disturbing forces.

## STATISTICS OF FINAL POSITION AND VELOCITY

In order to estimate the statistics of final position and velocity under open-loop control, we need to make some simplifying assumptions. The consequences of these assumptions need to be carefully assessed when making actual applications. For the autoloader, these assumptions seem to be reasonable.

We assume first that the disturbing forces in each of the three open-loop sections of Figure 7 are statistically independent random variables, which are constant in each section during any given cycle. These forces vary randomly, however, from cycle to cycle. We also assume that the disturbing forces are composed of a friction term that is dependent on the sign of the velocity and another constant force term such as gravity or motion coupling. This covers many practical cases including application to the large caliber autoloader. It is summarized as follows:

$$\tilde{u}_{di} = \tilde{u}_{gi} - sign(\dot{x})\,\tilde{F}_i \quad = \text{disturbing force for the } i\text{th section} \tag{3}$$

in which

| | | | |
|---|---|---|---|
| | $i$ | = | open-loop section number |
| | tilde (~) | = | a sample outcome of a random variable, which is constant during a given cycle |
| | $F_i$ | = | friction force for section $i$ |
| | $u_{gi}$ | = | gravity and/or coupling force for section $i$ |

The random disturbing forces are assumed to be $s$-normally distributed with $s$-means and $s$-variances $\bar{F}_i$, $\sigma^2_{F_i}$, $\bar{u}_{gi}$, $\sigma^2_{u_{gi}}$. These are to be estimated for an actual system during closed-loop MBB operation. If we assume the disturbing forces to be equal to their average values, we can calculate representative times $t_i$ of constant motor force application by applying the equation of motion, equation (1), within each open-loop section. These representative times and the associated constant motor force $u$ are given as follows:

$$t_1 = m v_m / [u_1 - (\bar{F}_1 - \bar{u}_{g1})] \;;\quad u = u_1 = \text{maximum acceleration motor force}$$

$$t_3 = m v_m / [u_3 + (\bar{F}_3 - \bar{u}_{g3})] \;;\quad u = -u_3 = \text{maximum deceleration motor force} \tag{4}$$

$$t_2 = \frac{x_r}{v_m} - \frac{1}{2}(t_1 + t_3) \;;\quad u = u_2 = -\bar{u}_{g2} + \bar{F}_2 = \text{force required to maintain constant velocity } v_m$$

The variable $v_m$ is the specified maximum velocity for MBB operation.

If in any given run the actual disturbing forces are equal to their average values, then the times given by equation (4) will yield the ideal response shown in Figure 7. In this case, the final position will be equal to $x_r$ and the final velocity will be zero. However, using the times in equation (4) when the disturbing forces are random will yield random values for final position and velocity. Being able to estimate the statistics of the final position and velocity for the random case would permit the design of a conservative open-loop controller. The controller is conservative in the sense that we can respecify the target position to be something less than the desired target using statistics. The goal is to prevent excessive overshoot or inadvertent crashing of the mechanism.

The statistics of final position and velocity can be estimated using Monte Carlo simulation and theory. We will first discuss Monte Carlo simulation and then derive theoretical estimates.

In Monte Carlo simulation, sample outcomes of the disturbing forces are generated randomly assuming the $s$-normal distribution. The position and velocity at the end of each section of Figure 7 can then be calculated by solving equation (1) for constant forces. By generating a large number of samples in this manner, we can calculate the $s$-mean and $s$-variance of the final position and velocity. All that is required here is to solve equation (1) over and over again using different random values of disturbing forces and then calculate the statistics of final position and velocity.

Assume for any given sample outcome that the disturbing forces are given as $\tilde{F}_i$ *and* $\tilde{u}_{gi}$ for $i = 1, 2,$ and 3. Calculations of positions and velocities at the end of the different sections in Figure 7 are presented as follows:

Section 1:
$$\tilde{v}_1 = \frac{t_1}{m}[u_1 - (\tilde{F}_1 - \tilde{u}_{g1})]$$

$$\tilde{x}_1 = \frac{t_1^2}{2m}[u_1 - (\tilde{F}_1 - \tilde{u}_{g1})] \tag{5}$$

Section 2: $\bar{v}_2 = \frac{t_2}{m}[u_2 - (\bar{F}_2 - \bar{u}_{g2})] + \bar{v}_1$

$$\bar{x}_2 = \frac{t_2^2}{2m}[u_2 - (\bar{F}_2 - \bar{u}_{g2})] + t_2\bar{v}_1 + \bar{x}_1 \qquad (6)$$

Section 3: The velocity $v_3(t)$ can go negative in this section. When it does, the friction force changes sign. The total force $u_t$ acting on the mass $m$ consequently changes as follows:

$$u_t = u_t^- = [-u_3 - \bar{F}_3 + \bar{u}_{g3}] \qquad for\ v_3(t) \geq 0.0$$

$$= u_t^- = [-u_3 + \bar{F}_3 + \bar{u}_{g3}] \qquad for\ v_3(t) < 0.0 \qquad (7)$$

For a given run, we calculate the time $t = \bar{t}_c$ when $v_3(t) = 0.0$ where up to this point $u_t = u_t^-$ :

Crossover time = $\bar{t}_c = m\,\bar{v}_2 / [u_3 + (\bar{F}_3 - \bar{u}_{g3})]$ .

$$\bar{v}_3 = \frac{t_3 u_t^-}{m} + \bar{v}_2; \qquad if\ \bar{t}_c \geq t_3$$

$$= \frac{(t_3 - \bar{t}_c)\,u_t^-}{m}; \qquad if\ \bar{t}_c < t_3$$

$$\bar{x}_3 = \frac{t_3^2 u_t^-}{2m} + \bar{v}_2 t_3 + \bar{x}_2; \qquad if\ \bar{t}_c \geq t_3$$

$$= \bar{x}_c + \frac{(t_3 - \bar{t}_c)^2 u_t^-}{2m}; \qquad if\ \bar{t}_c < t_3 \qquad (8)$$

where $\bar{x}_c = \frac{\bar{t}_c^2 u_t^-}{2m} + \bar{v}_2 \bar{t}_c + \bar{x}_2$ .

Section 4: This is an added section to open-loop operation and is a result of the fact that the velocity at the end of section 3 is generally not equal to zero. The motor force is set to zero, but motion continues until friction eventually stops the motion. If the friction force in section 4 is assumed to be equal to its value for section 3, $\bar{F}_3$, we get the following final position and velocity:

$$\bar{v}_f = 0.0$$

$$\bar{x}_f = \bar{x}_3 - \frac{m\,\bar{v}_3^2}{2\,u_t} \tag{9}$$

in which $u_t = -\bar{F}_3 + \bar{u}_{g3}\,; \quad \bar{v}_3 \geq 0.0$

$$u_t = +\bar{F}_3 + \bar{u}_{g3}\,; \quad \bar{v}_3 < 0.0$$

We conducted a number of Monte Carlo trials using the above solutions. We used our own computer program to perform the simulations. Each set of Monte Carlo trials involved the following steps:

1. Fix the system parameters $m$, $u_m$, $v_m$, $\bar{F}_i$, $\sigma^2_{F_i}$, $\bar{u}_{gi}$, $\sigma^2_{u_g}$, and $x_r$.

2. Generate random sample outcomes of the disturbing force terms $\bar{F}_i$ *and* $\bar{u}_{gi}$ for each of the three open-loop sections using a random number generator.

3. Calculate the final position $\bar{x}_f$ using equations (4) through (9).

4. Repeat steps 2 and 3 $n$ times; for example, 1000 times.

5. Calculate the $s$-mean and $s$-variance of $\bar{x}_f$ for the $n$ trials.

The Monte Carlo simulation just described is a time-consuming computational procedure. Consequently, it cannot be readily conducted in real-time during the operation of an actual system. What we need is an acceptable faster solution. We derived such a solution theoretically by making some additional simplifying assumptions to those made for the Monte Carlo approach. We then compared these theoretical solutions to the Monte Carlo results.

The additional assumptions involve the following: First we assume that the velocity remains positive (or of constant sign) throughout the cycle. The fact that it can go negative near the end of the cycle will be assumed negligible. This assumption means that we can treat disturbing forces as constants throughout. Residual velocity $\bar{v}_3$ at the end of the operating cycle will also be assumed negligible so that $\bar{x}_f = \bar{x}_3$. Combining equations (4) through (8), using these additional assumptions, we can calculate $\bar{x}_f$ directly as a function of the disturbing forces and the section times $t_i$:

$$\bar{x}_f = \bar{x}_3 = x_r + C_1(\bar{u}_{d1} - \hat{u}_{d1}) + C_2(\bar{u}_{d2} - \hat{u}_{d2}) + C_3(\bar{u}_{d3} - \hat{u}_{d3}) \tag{10}$$

in which $C_1 = \frac{1}{m}\left(\frac{t_1^2}{2} + t_1 t_2 + t_1 t_3\right)$

$$C_2 = \frac{1}{m}\left(\frac{t_2^2}{2} + t_2 t_3\right)$$

$$C_3 = \frac{1}{m}\frac{t_3^2}{2}$$

For this case $\bar{\bar{x}}_f = x_r$, the target position and for $s$-independent disturbing forces in the three open-loop control sections,

$$\sigma_{x_f}^2 = C_1^2\sigma_{u_{d1}}^2 + C_2^2\sigma_{u_{d2}}^2 + C_3^2\sigma_{u_{d3}}^2 \tag{11}$$

Table 1 lists some results for a particular autoloader example derived from both Monte Carlo simulation and theoretically using equation (11). Friction forces $F_i$ are the only disturbing forces assumed in this particular example. For these cases $m$ = 80 lbs/$G$, $G$ = 386 in./sec$^2$, $v_m$ = 120 in./sec, $x_r$ = 115 inches, and the maximum motor force allowed $u_{max}$ = 75 lbs. For the Monte Carlo trials, a sample size of $n$ = 1,000 was used for each case.

**Table 1. Monte Carlo Simulation and Theoretical Calculation of Standard Deviation of Final Position**

| $\bar{F}_1$ lbs | $\sigma_{F1}$ lbs | $\sigma_{F2}$ lbs | $\sigma_{F3}$ lbs | $\sigma_{x_f}$ | |
|---|---|---|---|---|---|
| | | | | Simulation | Eq.(11) |
| 10 | 1.0 | 1.0 | 1.0 | 2.875 | 2.732 |
| 20 | 1.0 | 1.0 | 1.0 | 2.924 | 2.887 |
| 30 | 1.0 | 1.0 | 1.0 | 3.260 | 3.201 |
| 30 | 1.0 | 0.0 | 0.0 | 2.896 | 2.871 |
| 30 | 0.0 | 1.0 | 0.0 | 1.442 | 1.410 |
| 30 | 0.0 | 0.0 | 1.0 | 0.139 | 0.135 |
| 30 | 2.0 | 2.0 | 2.0 | 6.739 | 6.402 |

From the results shown in Table 1 and other results not shown here, we conclude that equation (11) can be used to adequately approximate the Monte Carlo results. Real-time estimation of open-loop parameters and conservative target positions can, therefore, be readily obtained in real-time during operation of a given system. Specifically, given the estimates of the statistics of the disturbing forces, we can quickly estimate the statistics of the final position for open-loop operation. From this information, we can calculate a conservative set of open-loop parameters as previously discussed by calculating a new target position $x_{r_o}$ less than $x_r$, which yields acceptable probability that $\tilde{x}_f \leq x_r$ for any given cycle run.

It could be mentioned again that the conservative open-loop controller being described here is intended to be used only as a degraded mode of operation in the event of feedback sensor malfunction. Closed-loop MBB control is the normal mode of operation.

In the next section, we briefly discuss how to estimate the disturbing forces in real-time from which we can calculate the statistics of final position for open-loop operation using equation (11).

## MEASUREMENT OF DISTURBING FORCES

In measuring disturbing forces, we first accumulate motor force, position, and velocity versus time data during closed-loop MBB operation of a system. We process this data to determine the beginning and end points of each of the three major motion sections: acceleration, constant velocity, and deceleration. We then estimate the disturbing forces in each section. Ideally, we would like to determine an equivalent constant disturbing force perhaps representing an average for each section so that we can estimate a constant motor force to be used in the open-loop mode. As a first approach, we will assume that disturbing forces are constant in each section but may differ in the different sections.

Assuming constant average forces within a section, we can calculate the disturbing forces using the following relations:

$$\bar{u}_{di} = \frac{m\,(\Delta\dot{x})_i}{(\Delta t)_i} - \bar{u}_i \tag{12}$$

in which $\bar{u}_i = \frac{1}{N_i}\sum_{k=1}^{N_i} u_k$

$u_k$ = motor force for the $k$th time increment

$N_i$ = number of sample time increments in the $i$th section

For sections 1 and 3, $(\Delta\dot{x})_i$ represents the change in velocity within these sections. In section 2, the change in velocity should be near zero so that the disturbing force is essentially equal to the average motor force.

## EXPERIMENTAL RESULTS FOR LARGE CALIBER AUTOLOADER

A typical closed-loop cycle for the autoloader rammer is shown in Figure 8, where we have indicated the three major control sections. The maximum force for this case is 75 pounds except for the first 12 inches of travel, where 110 pounds is required to overcome high initial friction forces. Besides friction, there are coupling disturbing forces between the rammer and telescoping cell that result in the more complicated motion profile shown in Figure 8.

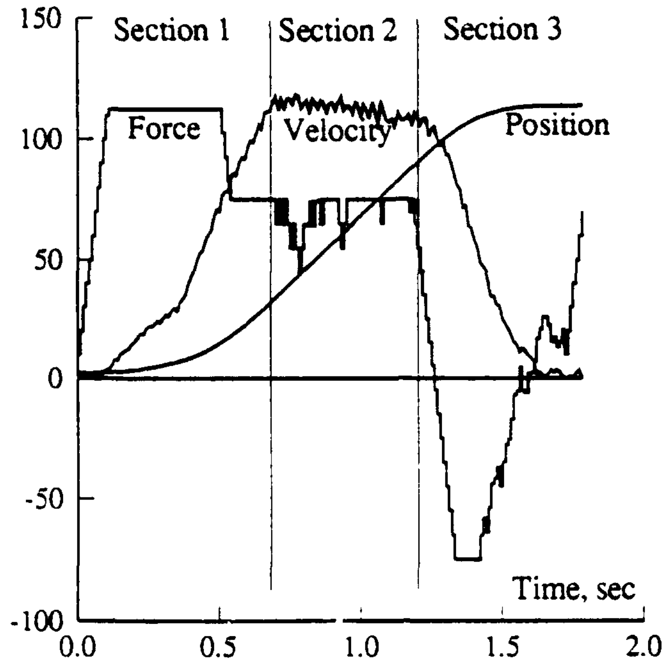


Figure 8. Closed-loop cycle for autoloader rammer showing three major control sections.

We conducted a number of trials applying the results reported herein. Table 2 lists some of the results obtained for the disturbing forces and their standard deviations for closed-loop MBB operation of the autoloader rammer. Equation (12) was used for calculating disturbing forces. The standard deviations in Table 2 are the s-unbiased sample deviations calculated for the number of trials shown. As can be seen, some variations exist between different sets of runs. These variations primarily reflect wear and current condition of the ramming mechanism. It is important then when applying open-loop control to use the latest data to reflect updated conditions. The rammer numbers shown in Table 2 indicate the use of two different rammer mechanisms.

**Table 2. Disturbing Forces and Standard Deviations for Autoloader Trials**

| Rammer Number | Trial Nos. | $u_{d1}$ lbs | $\sigma_{u_{d1}}$ lbs | $u_{d2}$ lbs | $\sigma_{u_{d2}}$ lbs | $u_{d3}$ lbs | $\sigma_{u_{d3}}$ lbs | $\sigma_{x_f}$ eq.(11) |
|---|---|---|---|---|---|---|---|---|
| 1 | 27-51 | 48.1 | 1.37 | 61.8 | 1.47 | 30.8 | 1.45 | 4.12 |
| | 301-320 | 52.6 | 1.23 | 66.1 | 2.33 | 31.2 | 3.14 | 4.36 |
| | 501-523 | 56.6 | 1.95 | 68.8 | 1.77 | 33.9 | 3.30 | 6.61 |
| 2 | 101-110 | 52.2 | 1.84 | 66.5 | 2.22 | 30.4 | 3.79 | 5.98 |
| | 301-310 | 52.5 | 1.61 | 64.4 | 3.11 | 27.3 | 1.97 | 5.74 |

We conducted a number of open-loop trials after closed-loop trials 301 to 310 for rammer #2. Figures 9, 10, and 11 show some of the results of these trials for three different values of conservative open-loop target position $x_{r_o}$. $x_{r_o}$ for these trials was estimated using equation (2) for three different values of $t_p$ = 1.0, 2.0, and 3.0. Comparison is made in these figures to the last closed-loop trial conducted prior to the open-loop trials.

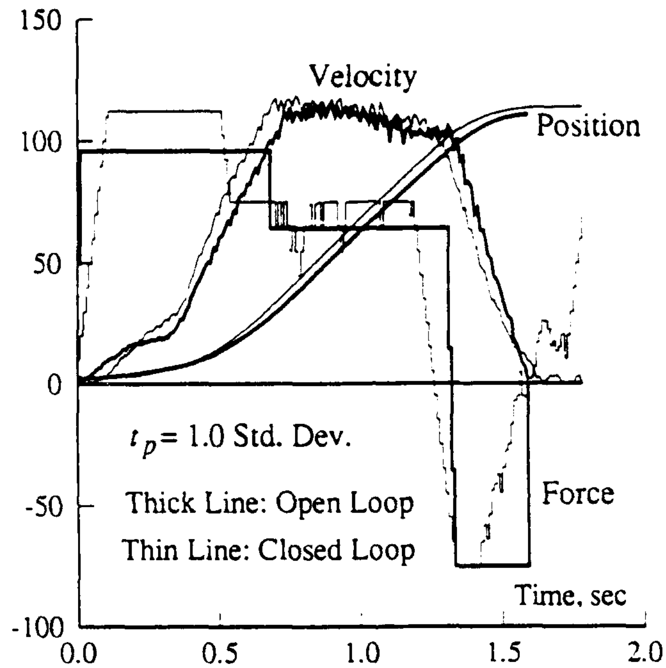



Figure 9. Open versus closed-loop trials for autoloader rammer with $t_p$ = 1.0.

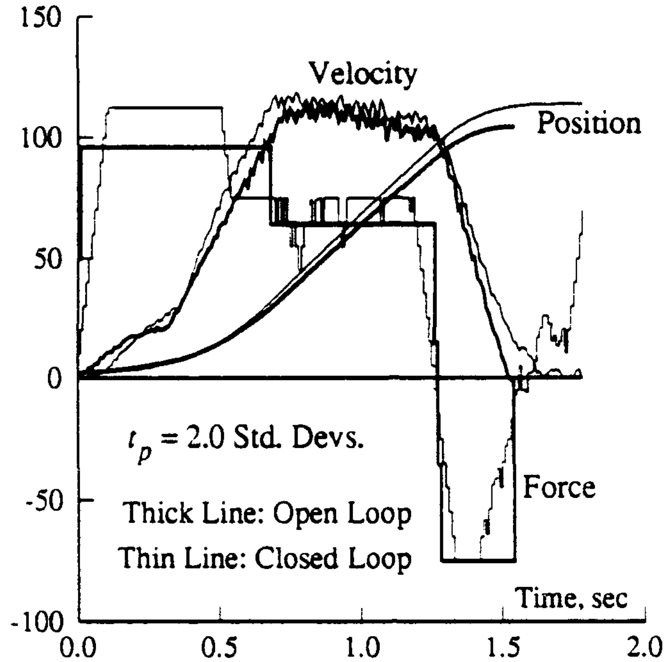



Figure 10. Open versus closed-loop trials for autoloader rammer with $t_p$ = 2.0.

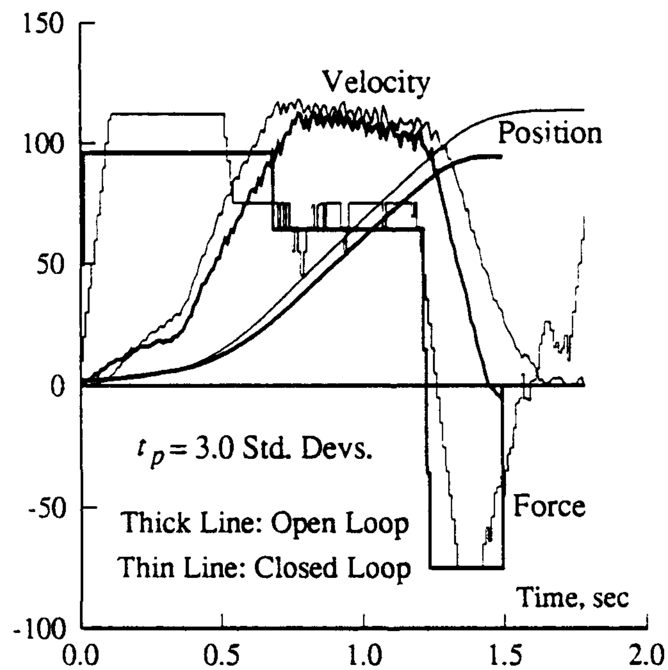



Figure 11. Open versus closed-loop trials for autoloader rammer with $t_p$ = 3.0.

The main problem that we experienced for these particular trials was in matching section 1, the acceleration phase. The average open-loop motor force used (96 pounds) did not accelerate the round of ammunition as fast as in the closed-loop trials. It appears that a higher motor force closer to the initial closed-loop 110 pounds needs to be used to match accelerations. However, the maximum velocity was closely achieved in all cases, but with a nearly fixed delay time for the open-loop trials. This delay was added to $t_2$ for the results shown in Figures 9 through 11. This yielded satisfactory results for all of our open-loop trials. Table 3 lists some of the final positions obtained for the open-loop trials.

**Table 3. Final Positions for Open-Loop Control of Autoloader Rammer**

| Run # | $t_p$ Std. Devs. | $\hat{x}_f$ inches | $x_{ro}$ inches | $x_r$ inches |
|---|---|---|---|---|
| 403 | 3.0 | 94.6 | 97.3 | 115.0 |
| 404 | 2.0 | 104.5 | 103.0 | 115.0 |
| 405 | 1.0 | 110.8 | 108.8 | 115.0 |
| 406 | 1.0 | 107.9 | 108.8 | 115.0 |

We found that a satisfactory procedure for finishing the ammo ramming function is to apply cyclic motor force with a peak of about 50 pounds until a switch is tripped indicating a successful loading. Application of open-loop procedures to both increase reliability and minimize instabilities will be incorporated into next generation tank autoloaders.

From the work conducted thus far, we conclude that the techniques for open-loop control presented are sound and applicable to real situations. This then provides an acceptable degraded mode of operation, which can increase the mission reliability by providing redundancy.

Using the modified bang-bang control law makes it easier to divide the motion cycle into the three sections of acceleration, constant velocity, and deceleration. However, other control laws can be used as long as estimates of disturbing forces can be made for the equivalent open-loop sections. It may also be possible to run a system in the open-loop mode for a major portion of the motion cycle. The stability advantages of running open-loop could consequently be realized for this case regardless of reliability considerations.

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